

Introduction: We currently have extensive data for four different terrestrial bodies of the inner solar system: Earth, the Moon, Mars, and the Eucrite Parent Body [EPB]. All formed early cores; but all(?) have mantles with elevated concentrations of highly siderophile elements, suggestive of the addition of a late “ve-neer”. Two appear to have undergone extensive differentiation consistent with a global magma ocean. One appears to be inconsistent with a simple model of “low-pressure” chondritic differentiation. Thus, there seems to be no single, simple paradigm for understanding early differentiation.

EPB. Currently, there is no evidence that eucrites are other than simple partial melts of a chondritic (CO-like) parent body. The agreement between phase equilibrium experiments on natural eucrites and devolatilized Murchison (CM) is remarkable. The most compelling reason for believing that eucrites might be the result of equilibrium or fractional crystallization of a more primitive magma is the desire to relate eucrites and diogenites (i.e., howardites). But at this juncture, no model has been able to produce such a relationship in a quantitatively satisfying way. Both partial melting experiments of chondrites and constraints from eucrite Sc/La ratios imply that eucrites were produced by ~20% partial melting of a CO-like source. Such a source is depleted in low-Ca pyroxene by 1200°C, with a maximum MgO content of ~En₇₀, whereas almost all diogenites have Mg#’s > 70. Experiments show that eucrites formed at IW-1, consistent with a chondritic ol-opx-metal assemblage.

The EPB differentiated very early while ¹⁸²Hf was still present (t_{1/2} = 9 m.y.). Therefore, eucrite petrogenesis occurred much less than 50 m.y. after CAI formation. Since the EPB appears to have experienced core formation, this means that core formation occurred at this time, or earlier.

Lithophile incompatible elements were quantitatively removed from the eucrite source regions. Incompatible element ratios in eucrites are generally chondritic.

The Moon. The Moon is the type locality for the magma ocean hypothesis. Mare basalts (and their source regions) are depleted in alumina and have negative Eu anomalies. Conversely, the highlands crust is enriched in plagioclase and has a positive Eu anomaly. Therefore, there is a natural complementarity between these two reservoirs, suggesting separation of a plagioclase component by floatation from a magma ocean.

Even if this separation occurred without the aid of a magma ocean, the chemical complementarity between the lunar highlands and the depleted mare source regions is undeniable. Melt was clearly extracted from the lunar interior early in its history, depleting the lunar mantle in incompatible elements. These incompatibles were concentrated into a reservoir known as KREEP. The uniformity of elemental ratios in KREEP is itself an argument for a magma ocean — i.e., a single event.

Model ages of KREEP are nearly concordant between several different chronometer systems: 4.35-4.45. This suggests that the magma ocean lasted about 200 m.y. Perhaps coincidentally, this is the age of lunar differentiation inferred from ¹⁴²Nd systematics. Therefore, there are hints that early lunar differentiation lasted for quite some time.

Unlike the EPB, ¹⁸²W anomalies in lunar samples are small to nonexistent. This suggests that, even though lunar differentiation was prolonged, it was not initiated until ¹⁸²Hf was nearly extinct. These observations would also be consistent with a Moon that differentiated quickly at ~4.35 b.y. and that inherited a small ¹⁸²W anomaly.

It is now generally believed that the Moon has a small core, consistent with the redox conditions inferred earlier.

Experiments show that lunar basalts formed near IW-1, similar to eucrites.

Unlike the EPB(?), there are enclaves of the lunar mantle that are probably quite fertile. For example, the REE pattern of the A15 Green Glass is rather flat. It is not chondritic and has a small negative Eu anomaly, but it is not strongly depleted in the LREE. This would make it more fertile than modern-day MORB mantle. Therefore, models of lunar differentiation must accommodate a wide range of incompatible element depletions. Note that the A15 Green is not KREEPy; so REE abundances were not established by a late-stage mantle overturn.

Mars. Mars differentiated early into core, mantle, and crust. This is established by the significant ¹⁸²W anomalies in martian meteorites. Like mare basalts and unlike eucrites, martian basalts all come from depleted source regions and it is inferred that this depletion also occurred very early.

There are at least two varieties of martian mantles: one that produced the nakhlites and chassignites and another that produced the shergottites. In particular, the shergottite mantle is so depleted that it is difficult

to understand how shergottite basalt generation occurs. In one model-dependent (but internally consistent) model, the nakhlite source region is twice as depleted in incompatibles as the terrestrial MORB mantle; and the shergottite mantle is three times more depleted still.

There is great similarity between the Lu-Hf and Sm-Nd systematics of shergottites on the one hand and high-Ti mare basalts and KREEP on the other. This suggests that, if the Moon went through a magma ocean stage, so did Mars.

The redox state of the martian mantle is not known precisely. However, Fe-Ti oxide assemblages in the most primitive shergottites [i.e., those with the highest initial $\varepsilon(\text{Nd})$] indicate an oxygen fugacity of $\sim\text{IW}$. And the similarity of FeO contents in basalts from the Moon, Mars and the EPB indicates that all three of these bodies were at $\sim\text{IW}-1$ at the time of core formation. And the shergottite mantle is near that value.

Because there are correlations between redox state and $\varepsilon(\text{Nd})$ within the shergottite suite, I believe the most oxidized shergottites have been influenced by crustal contamination. If so, then the martian crust is more oxidized than the martian mantle ($\sim\text{QFM}$).

The redox state of the nakhlite/chassignite mantle may also be more oxidizing. Wadhwa found no Eu anomaly in Nakhla clinopyroxenes; but Nakamura did. Wadhwa also found Eu anomalies in clinopyroxene from Chassigny. Therefore, the redox state of the nakhlite/chassignite mantle is uncertain. Even so, the similarity between the FeO contents of nakhlites and shergottites suggests that at the time of core formation, differences in redox states could not have been large.

Part of our uncertainty about nakhlites stems from the complex history of the nakhlite mantle. Comparison of the short- and long-lived chronometers in the Sm-Nd system indicates that, at some time in the past (~ 4 b.y.), the nakhlite mantle was refertilized. This is tricky and difficult to do, suggesting a differentiation event internal to the nakhlite mantle.

In summary, Mars differentiated very early into reservoirs that still exist today. The petrology of the martian mantle is complex but maybe less so than that of the Moon. The variation in redox state on Mars is, however, more complex than on the Moon.

Earth. Of course, the most complex planet of all is the Earth. And because of that, a great deal of its earliest history has been erased. Therefore, oddly, though we know more about the Earth than any other planet, it's earliest conditions are murky.

The Earth differentiated early to form a core. Tera has argued that this event occurred at 4.54 b.y. However, the arguments are complex to the non-plumbologist. But, if so, this predates the formation of

the mare basalt source regions by ~ 100 m.y. However, such an age may be consistent with the discovery of a small ($\sim 2\varepsilon$) ^{182}W anomaly in terrestrial rocks. Although if the core formed early, it is unclear why the W anomaly is not larger. Presumably either the core formed later than 4.54 b.y. or nonradiogenic chondritic W was added after core formation. In the latter case, it is unclear why this event is not recorded in the Pb system (i.e., why isn't the Pb age of the Earth younger?).

The redox state of the Earth is much more complicated than any other planet and is much beyond the scope of this abstract. There is an apparent paradox in that terrestrial rocks have less FeO than their extraterrestrial counterparts (~ 8 wt.% FeO). Taken at face value this means that core formation occurred under more reducing conditions ($\sim\text{IW}-2.5$). Yet, mantle rocks have oxygen fugacities of $\sim\text{QFM}$. How can these observations be reconciled?

Venus and the Earth have similar FeO contents, so there is a strong possibility that planet size (i.e., pressure) plays a role. Recent experiments, in fact, suggest that FeO may disproportionate into Fe metal and Fe^{3+} at pressures as low as ~ 250 kbar. If metal produced in this way segregates to the core, this could explain both the high- f_{O_2} of the upper mantle and its low FeO content. Further, thermodynamic calculations indicate that low pressure (< 30 kbar) pyrolite mineral assemblages at QFM would become more consistent with IW at higher pressures. Again, the main difference between Earth/Venus and the other terrestrial planets is size.

The extent to which the Earth has been differentiated is unclear. Oceanic basalts often have elevated $^3\text{He}/^4\text{He}$ ratios and solar Ne, suggestive of primordial signatures. In addition, fertile spinel lherzolites from continental lithospheres may show little evidence of substantial melt removal (i.e., they are still lherzolites). On the other hand, no mantle reservoir yet sampled has a chondritic Nb/U ratio, as expected for undifferentiated mantle. These observations, taken as a whole, argue for extensive but incomplete differentiation. A corollary of these observations is that there is no terrestrial evidence for a magma ocean (unlike the case of the Moon/Mars) or for a Moon-forming giant impact.

Another peculiarity of the Earth is that material has been returned to the mantle via subduction tectonics. This has allowed the transport of hydrous minerals to the mantle, which would otherwise be dry (like the other terrestrial planets).

And because the Earth has abundant surficial water, it may be the only planet with granitoid continents. Tonalites, the main component of ancient continental shields, are formed by the partial melting of altered (i.e., hydrated basalts).